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Exploring Nature-based Solutions on Refined Waterbird Habitats Restoration in High-density Urban Area: A Case Study of the Futian Mangrove National Important Wetland in Shenzhen, China

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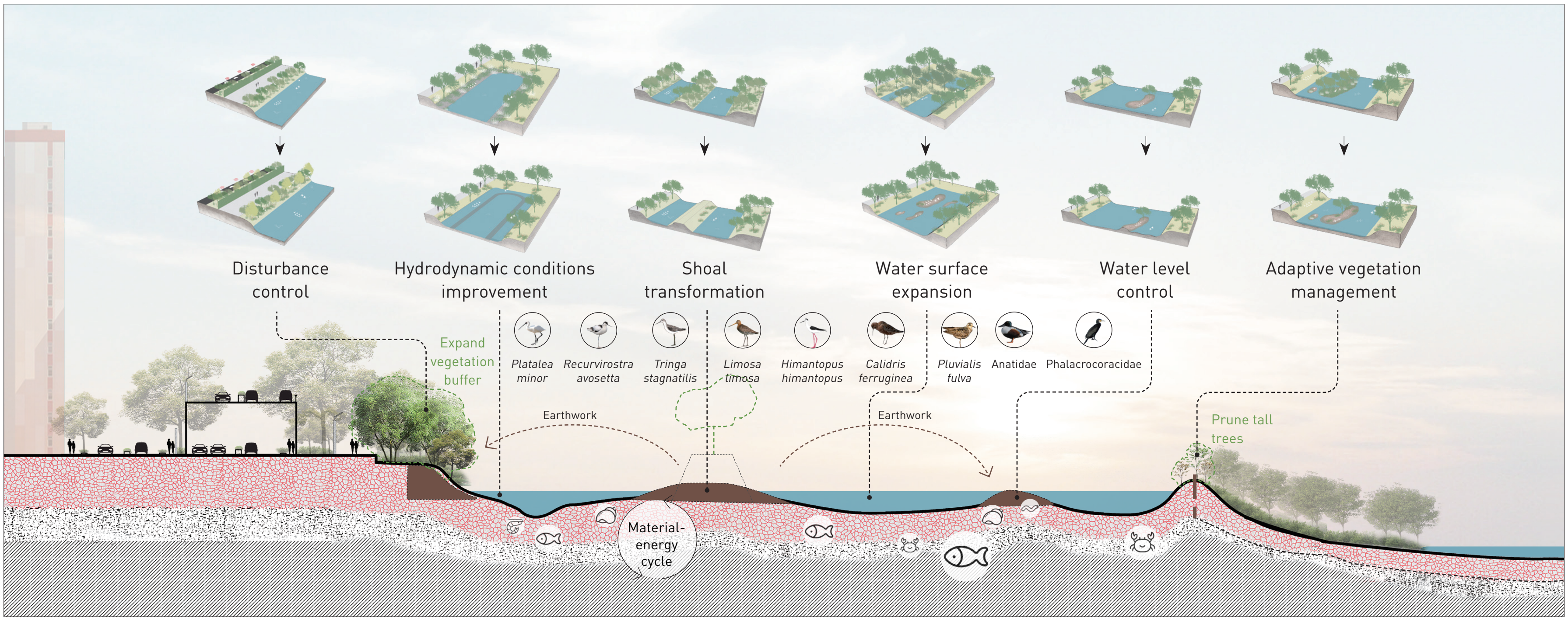
GRAPHICAL ABSTRACT



ABSTRACT

As a highly urbanized bay area bustling with socio-economic activities, Shenzhen Bay is a pivotal stopover and wintering habitat for migratory birds along the East Asian-Australasian Flyway. The Futian Mangrove National Important Wetland, located in the northeast of Shenzhen bay, is a part of the Guangdong Neilingding–Futian National Nature Reserve. As the smallest national nature reserve in China, the wintering habitat of migratory birds has been significantly impacted by the compacted surrounding built-up environment. It has become an urgent need for refined high-quality ecological restoration for the habitats. This project leveraged Nature-based Solutions to develop a refined model for the ecological restoration of coastal wetland waterbird habitats in compact urban areas. By analyzing waterbird behaviors and habitat requirements, this model outlined six strategies: water surface expansion, water level control, hydrodynamic conditions improvement, shoal transformation, adaptive vegetation management, and disturbance control. To effectively guide the restoration implementation, high-, medium-, and low-adaptive approaches were proposed accordingly. After restoration in 2022, notable increases in target species, such as *Platalea minor*, were observed. The variety of waterbirds of the reserve in 2022 increased by 33% compared with 2021, while increased by 50.9% compared with 2016, significantly enhancing ecosystem services of the coastal area. As urban renewal in China is shifting towards spatial redevelopment, this model offers valuable insights for ecological restoration aiming at coastal wetland waterbird conservation across the country, and substantially supports establishing the "International Mangrove Center" in Shenzhen.

KEYWORDS

Nature-based Solutions; Coastal Wetland; Ecological Restoration; Waterbird Habitat; Biodiversity

HIGHLIGHTS

- Explores Nature-based Solutions on refined coastal wetland restoration in highly urbanized area
- Summarizes the universal habitat requirements for five categories of waterbirds
- Proposes six ecological restoration strategies for waterbird habitats and corresponding high-, medium-, and low-adaptive approaches

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1 Background

Waterbirds are highly sensitive to ecological changes in coastal cities[1][2]. The area and quality of coastal wetlands significantly influence the biodiversity of local waterbirds and the population of migratory birds using these areas for stopovers[3]. Urban development in coastal regions, marked by dense construction and intense human activities, has led to a pronounced artificial transformation with decreasing coastal wetlands. This degradation substantially impacts waterbird habitats, resulting in notable declines in both the population and species of migratory birds[1]. In compact coastal urban regions like the Guangdong–Hong Kong–Macau Greater Bay Area, it is challenging to expand coastal wetlands and waterbird habitats. Thus, refined restoration of existing habitats has become crucial for improving biodiversity and ecological resilience in such regions.

Currently, research and practice on restoring coastal wetlands for waterbirds are increasing. The key technical methods include terrain modification, noise abatement, vegetation planting, food supplementation, and water system construction[4]~[14]. For instance, David J. Yozzo et al. advocated for using dredged materials to create artificial coral reefs for restoring bird habitats, intertidal marshes, mudflats, and bird islands[7]. These approaches can significantly enhance local waterbird diversity. However, some focus primarily on the development and management of constructed wetlands with immediate outcomes, rather than on restoring the tidal regulation functions of natural wetlands via natural processes[15][16]. With various physical traits and living habits, different waterbird species require varied ecological habitat environments: Anatidae prefer open waters with soft sand and mud shoals, part of the sand and gravel substrate with complex structures, and deep waters without vegetation; in contrast, Ardeidae are inclined towards habitats in waters near trees[17]. Therefore, it is imperative to implement detailed restoration to address the needs of different waterbirds[5]. Existing habitat restoration methods have limited consideration of target waterbird species with simplistic need analysis, lacking multi-objective solutions that cater to the varied habits of diverse waterbird species.

Nature-based Solution (NbS) has gained prominence as an effective way to address climate change and bolster resilience in recent years. NbS underscores the significance of protecting, managing, or establishing new ecosystems to implement and utilize natural functions, offering cost-effective and adaptable solutions to complex social challenges[18]~[20]. The adoption of NbS spans a wide array of fields including biodiversity conservation, wetland restoration, and protection of river ecosystems[8][21][24], showcasing extensive research and practices. However, its integration into refined avian habitat restoration is still nascent. For instance, the coastal wetland restoration project in Yancheng, Jiangsu Province, China created functional zones including bird refuge zone, swimming bird foraging zone, wader bird foraging zone, fish refuge zone, and ecological buffer zone[8]; the restoration of polders of Jianyang Lake Wetland in Zhejiang Province, China, adopted a "retaining–breaking–integrating" design concept to construct a complex wetland ecosystem composed of forest, pond, farmland, lake, and island to improve habitats for Ardeidae[24]; the West Pond Living Shoreline Project in Jamaica Bay, New York City, USA, incorporated oyster shell breakwater structures, additional sediment, marsh planting, and erosion control to provide habitat for endangered species and migratory birds[25]; the Mid-Barataria Sediment Diversion Project Final Restoration Plan in Louisiana, USA proposed to rejuvenate coastal wetland habitats and ecosystem functions by re-establishing the connection between the Mississippi River and the Barataria Basin estuary[26]; the Greater Niagara Region, Canada applied Ecosystem-based Adaptation to conserve waterbird diversity via living shoreline and beach sand replenishment[27]. While these cases exemplify the application of NbS, practical implementation of these plans remains at a preliminary stage, lacking refined models or approaches. Employing NbS to develop methods for restoring coastal waterbird habitats has significant potential for further development. Thus, taking the restoration design project of the Futian Mangrove National Important Wetland in Shenzhen as a case study, this paper explores Nature-based Solutions on refined waterbird habitats restoration. It aims at theoretical and technical innovation in coastal wetland ecological restoration, enriching the practical experience of NbS application in bird conservation.

2 Study Site and General Model for Restoration

2.1 Futian Mangrove National Important Wetland in Shenzhen

The Futian Mangrove National Important Wetland in Shenzhen ("Futian Mangrove Wetland" hereafter) is a quintessential example of waterbird habitats in high-density coastal cities in China. Located in the Futian District of Shenzhen City, Guangdong Province, and adjacent to the Mai Po Wetland of Hong Kong, it is an integral part of the Neilingding–Futian National Nature Reserve. It has been selected in the "*2020 National Important Wetland List*" and designated as a "wetland of international importance" under the *Ramsar Convention*[28]. On November 5, 2022, the establishment of the "International Mangrove Center" in Shenzhen was announced on the 14th Meeting of the Conference of the Parties to the *Ramsar Convention*[29], with the Futian Mangrove Wetland being a key initiative.

The Futian Mangrove Wetland is a critical overwintering and stopover site on the East Asian–Australasian migration route, which is essential to global bird conservation. According to the Guangdong Neilingding Island–Futian National Nature Reserve Administration ("Reserve Administration" hereafter), every year, hundreds of thousands of waterbirds stop in Shenzhen Bay, including 13 species listed on The International Union for Conservation of Nature (IUCN) Red List of Threatened Species, such as *Platalea minor* and *Limosa limosa*.

The core of Futian District in Shenzhen is among the most urbanized areas along China's coastline, characterized by high construction intensity, tall buildings, and vibrant activities of various groups of people, significantly affecting the overwintering of migratory birds. As China's only national nature reserve within core urban area, the wetland lacks a buffer zone from the built-up surroundings, thus confining the range of conservation; and the north of the reserve is adjacent to the Binhai Avenue and the Beijing–Hong Kong–Macao Expressway, where traffic notably impacts bird populations, making protection on the reserve under considerable pressure[30]. Forming the ecosystem of the Futian Mangrove Wetland together with the periphery mudflats and mangroves, the dike-ponds are pivotal high-tide habitats for migratory birds. Achieving high-quality restoration of these dike-ponds within the limited space of the Futian Mangrove Wetland has become a major challenge. Moreover, as China's urban renewal has shifted towards refined redevelopment, exploring NbS on refined ecological restoration offers substantial support and guidance for better quality and efficiency in these endeavors.

2.2 Site Condition

According to remote sensing data from the Reserve Administration, the total area of fishponds in the Futian Mangrove Wetland is approximately 63.17 hm^2, consisting of 12 dike-ponds and 1 typhoon shelter pond. Upon years of continuous restoration, 27.10 hm^2 of the area (Fishponds No. 1 ~ 4 along the west bank of the Fengtang River) have been restored before 2022. The project in this paper focused on the comprehensive restoration of fishponds on the east bank (Table 1), including Fishponds No. 5 ~ 11, the Northern Freshwater Pond, and the Typhoon Shelter Pond, covering a total area of 36.07 hm^2. The restoration of primary zones has been completed during March to September 2022, covering Fishponds

No. 5 and 6, the Northern Freshwater Pond, and the Typhoon Shelter Pond (Fig. 1), effectively integrating Fishponds No. 1 ~ 6 on both banks for ecological management enhancement.

2.3 Overall Restoration Model

Drawing on research and practical experience, this project establishes an overall restoration model for waterbird habitats (Fig. 2) in the Futian Mangrove Wetland. Initially, combine existing monitoring data with field observations to determine target waterbirds, and analyze the habitat needs of these birds through literature review and bird behavior observations. Then, conduct a site suitability analysis and problem diagnosis on water surface area, water depth, hydrodynamic conditions, shoal and islet morphology, the effects of plants, and the effects of urban and human activities, to propose refined ecological restoration models for target waterbirds. Finally, based on the specific site conditions, develop six strategies that includes high-, medium-, and low-adaptive approaches for implementation.

3 Site Assessment Based on Habitat Needs of Target Waterbirds

3.1 Bird Resource Analysis

Bird resource analysis was conducted combining monitoring data in past years and field observations. According to the data from the Reserve Administration, a total of 261 bird species from 60 families of 20 orders had been recorded within the Futian Mangrove Wetland by 2021. Among them, 13 species are under national

Table 1: Habitat conditions of fishponds along the east bank of the Fengtang River

Fishpond	Area (hm^2)	Number of small ponds	Water depth (m)	Habitat condition
No. 5	6.85	5	1 ~ 1.5	· Embankment vegetation dominated by tall trees with numerous invasive plants · The northern water surface is encroached by *Phragmites australis*
No. 6	3.46	4	1.5 ~ 2	· Embankment vegetation dominated by trees and shrubs with numerous invasive plants · The water body is narrow and elongated, easily disturbed by external factors
No. 7	5.11	4	1.5 ~ 2	· Rich embankment vegetation with numerous invasive plants · Significantly impacted by urban traffic noise and light
No. 8	3.93	2	2 ~ 2.5	· Rich embankment vegetation with numerous invasive plants · Islets within the pond
No. 9	4.95	4	2 ~ 2.5	· Rich embankment vegetation with numerous invasive plants · The water body is divided by cruciform embankments with tall trees
No. 10	3.94	3	1 ~ 2	· *Phragmites australis* are abundant in the central area, with numerous invasive plants · The eastern part is gradually terrestrializing, without tidal channels outwards
No. 11	2.74	0	2 ~ 2.5	· Lush embankment vegetation dominated by tall trees · Islets with established groves within the pond
Northern Freshwater Pond	4.30	5	0.3 ~ 0.5 (dry season), 1 (rainy season)	· Lush embankment vegetation enclosed by tall, dense plants, with the water surface encroached by aquatic plants · Without tidal channels outwards, rainwater is easily accumulated
Typhoon Shelter Pond	0.79	0	Varies with tidal level	The water surface is covered *by Acanthus ilicifolius*

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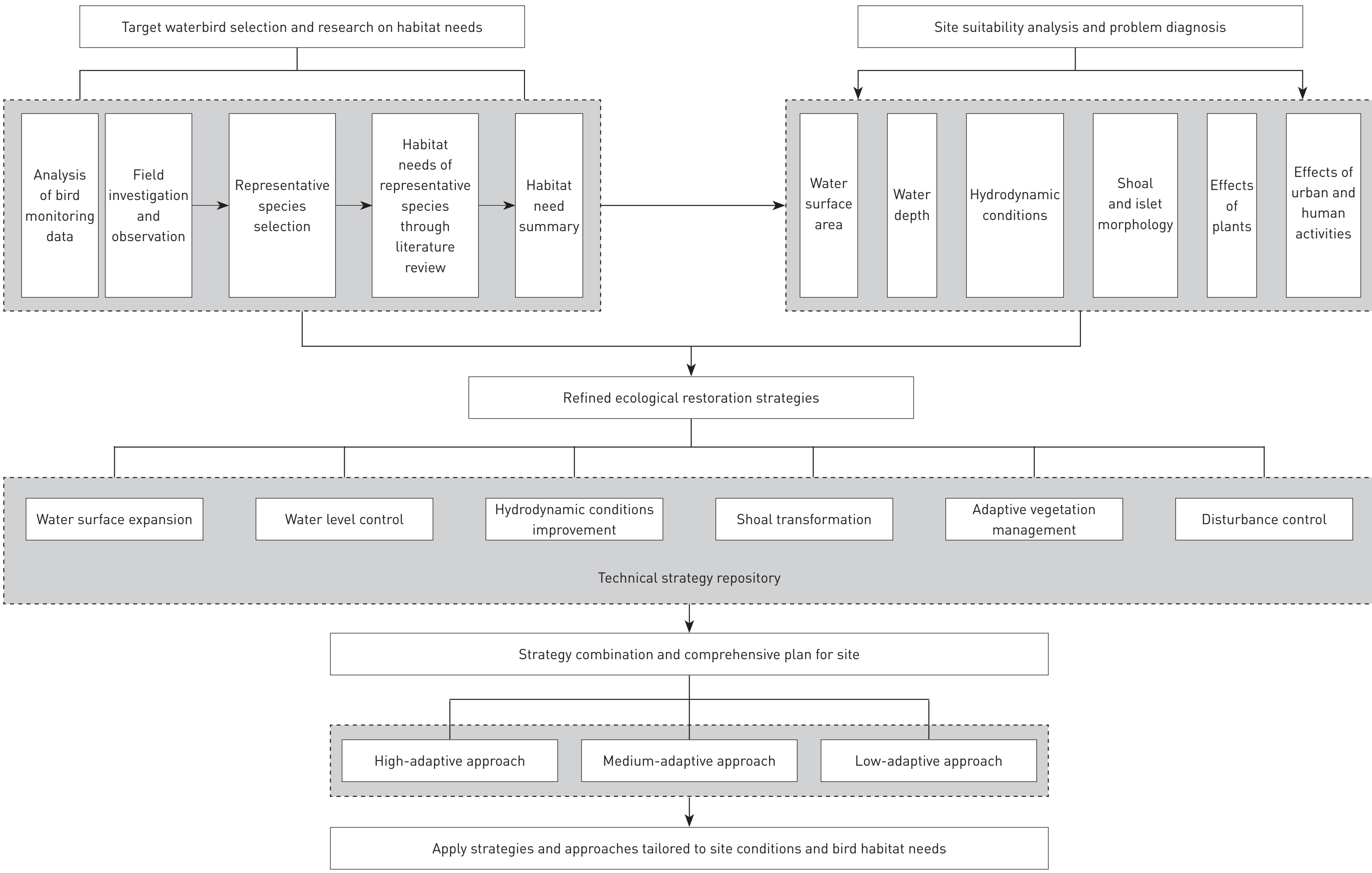

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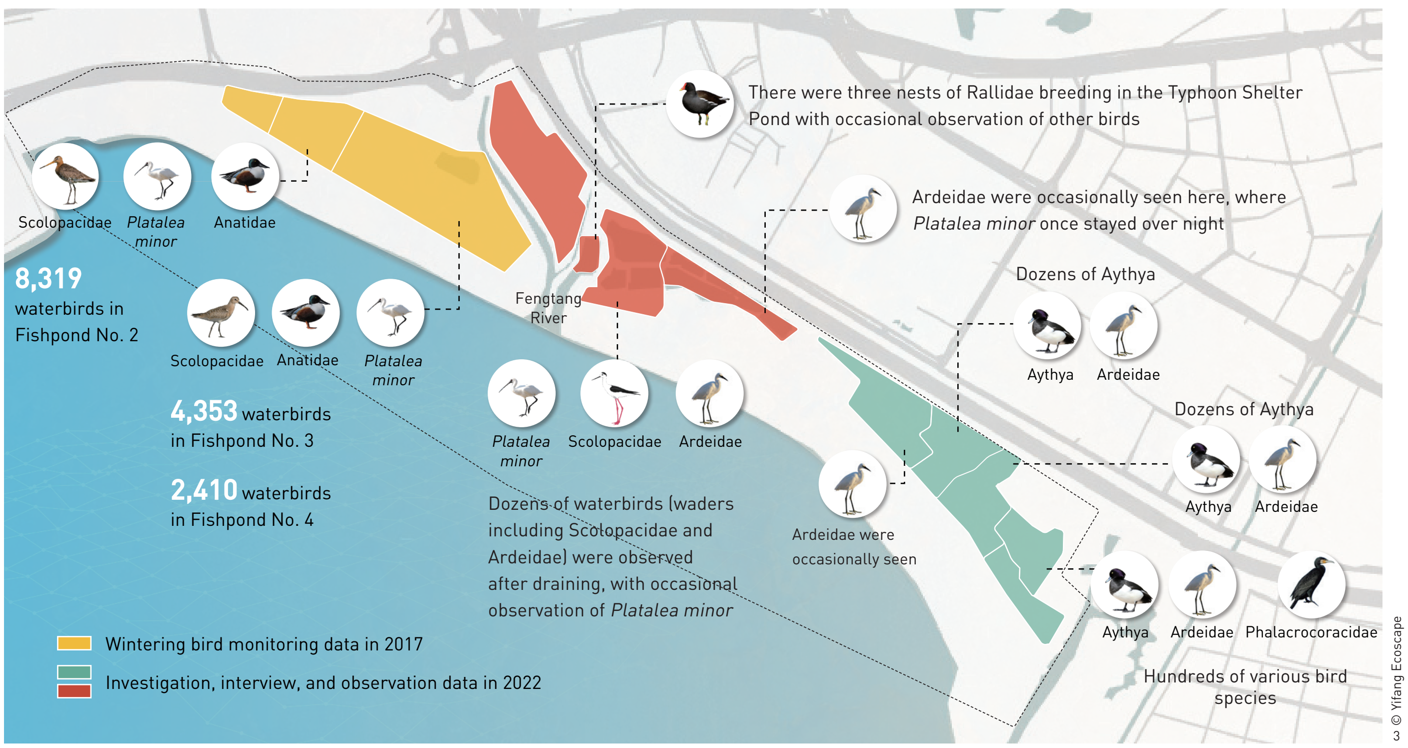
first-class protection, including *Platalea minor*, *Aythya baeri*, *Tringa guttifer*, *Egretta eulophotes*, *Threskiornis melanocephalus*, *Pelecanus crispus*, *Ciconia nigra*, and *Ciconia boyciana*, while 46 species under national second-class protection. The *Platalea minor* is listed as Endangered (EN) on The IUCN Red List of Threatened Species, the population of which in Shenzhen Bay remarkably exceeds 1% of its global population, making it one of star birds in Shenzhen.

According to the *Futian Mangrove Reserve Fishponds No. 1 ~ 11 Bird Monitoring Report (2015–2018)*, a total of 75,549 birds from 120 species were recorded during June 2015 to April 2018, which is fewer in summer and more in winter. The monitored birds mainly included Scolopacidae (approximately 75%), Anatidae (approximately 13%), Ardeidae, Rallidae, and Phalacrocoracidae, with dominant species including *Recurvirostra avosetta*, *Tringa totanus*, *Himantopus himantopus*, *Tringa nebularia*, *Calidris ferruginea*, *Tringa stagnatilis*, *Pluvialis fulva*, *Anas clypeata*, and *Anas crecca*. As the fishponds on the east bank of the Fengtang River had not been restored then, the waterbirds primarily inhabited the restored Fishponds No. 2 ~ 4 according to winter bird observation data from 2017 to 2018 (8,319 recorded in Fishpond No. 2, 4,353 in Fishpond No. 3, and 2,410 in Fishpond No. 4) (Fig. 3).[31]

To confirm the distribution of waterbirds on-site before the restoration of the east bank fishponds, the project team conducted line transect survey on January 12 and January 19, 2022. Transects were established around the periphery of the fishponds. The team made walking observations along the predetermined route when the tide in Shenzhen Bay was high (above 1.5 m), recording both the water levels of the fishponds and the behaviors of waterbirds. The survey revealed that there were over 50 waterbirds each in Fishponds No. 8, 9, and 11, while the other fishponds had around 10 each, primarily *Aythya fuligula*, *Egretta garzetta*, *Anas clypeata*, and a few *Himantopus himantopus* and *Platalea minor*, aligning with the results of historical records.

3.2 Habitat Needs Analysis of Target Waterbirds

Based on the monitoring data and field observations, Scolopacidae, Anatidae, Ardeidae, Rallidae, and Phalacrocoracidae, and one national first-class protected species (*Platalea minor*) have been identified as target waterbirds within the Futian Mangrove Wetland. Considering factors covering body length, ecological type, and residency type, representative species of the target waterbirds with relatively large population size on-site were selected (Table 2) to analyze their spatial preferences and human disturbance tolerance, which help determine the essential habitat needs and related indicators.



1. Fishpond locations in the reserve.
2. Refined ecological restoration model for waterbird habitats in high-density urban area.
3. Waterbird distribution before restoration.

Table 2: Overview of representative species of target waterbirds

Target waterbird		Representative species	Body length (cm)	Ecological type	Residency type	Human disturbance tolerance
Scolopacidae	Small	*Calidris ferruginea*	18.0 ~ 23.0	Wading bird	Transient birds	High
	Medium and large	*Limosa limosa*	36.0 ~ 44.0	Wading bird	Winter visitors	High
Anatidae	Non-diving	*Anas clypeata*	44.0 ~ 51.0	Swimming bird	Winter visitors	Medium to high
	Diving	*Aythya fuligula*	40.0 ~ 47.0	Swimming bird	Winter visitors	High
Ardeidae		*Egretta garzetta*	55.0 ~ 65.0	Wading bird	Mainly winter visitors, a few summer visitors and residents	Medium
Rallidae		*Gallinula chloropus*	30.0 ~ 38.0	Wading bird	Winter visitors with some residents	High
Phalacrocoracidae		*Phalacrocorax carbo*	84.0 ~ 90.0	Swimming bird	Winter visitors	High
National first-class protected species		*Platalea minor*	60.0 ~ 78.5	Wading bird	Winter visitors	High

NOTE
The information is sourced from Dongniao website, interviews with Reserve Administration, and field observation.

Research indicates that, apart from the special needs of each species, waterbird habitats generally require large, continuous open water surfaces for flocking and safety needs; shallow water for foraging; and a certain proportion of shoals and islets for resting and stopping, with a few aquatic vegetation patches around (without tall trees) and minimal noise disturbance (Table 3, Fig. 4).

3.3 Habitat Problem Diagnosis

According to the habitat needs of waterbirds above, a suitability analysis was conducted on the dike-ponds of the Futian Mangrove Wetland, assessing water surface area, water depth, hydrodynamic conditions, shoal and islet morphology, the impacts of vegetation, and the disturbance by human activities. It identified six common problems faced by the unrestored fishponds.

(1) Small water surface

The area of open water surface is one of the crucial factors affecting the utilization of waterbird habitats. In terms of total area, most fishponds on the east river bank range from 3 to 5 hm^2, which theoretically meets the needs of large, continuous open water surfaces for gregarious lifestyle (e.g., 2 ~ 3 hm^2 for Scolopacidae), but actually failed due to the water surface division into parts of about 1 hm^2 by embankments.

(2) Deep water level

Water depth is an important factor that influences bird's resting and foraging behaviors, and determines the diversity of waterbird species in wetlands. The water depth of most fishponds was around 2 m, deepening gradually from south to north, and from west to east, where the depth of Fishponds No. 8, 9, and 11 on the east bank were approximately 2.5 or 3 m.

(3) Weak hydrodynamic conditions

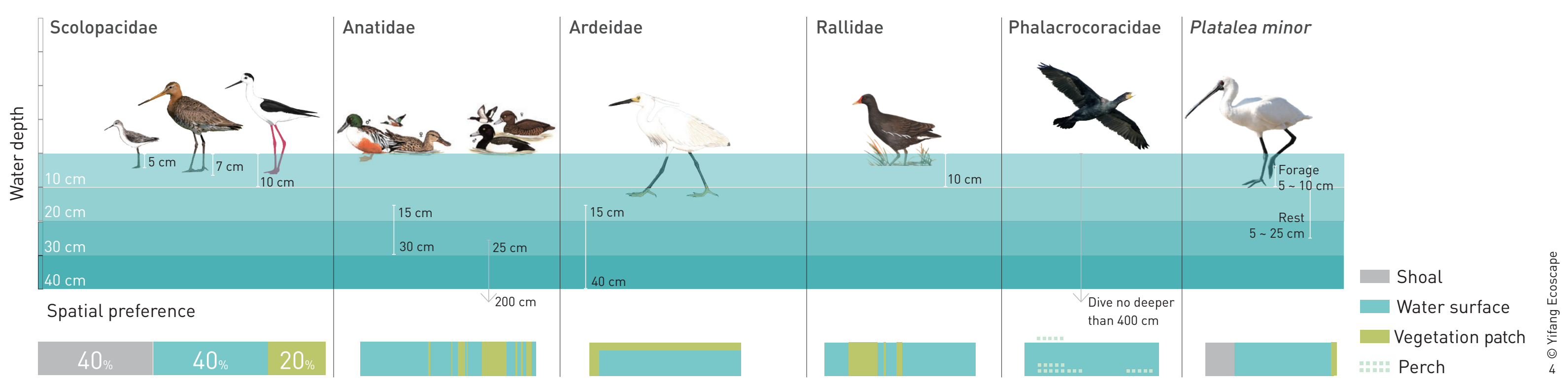
The exchange of materials and energy between the fishponds and Shenzhen Bay mainly relies on tidal channels, with water gates built over the channels to regulate water levels. The current water gates, constructed before 2008 with traditional lifting mechanisms, were elevated above the waterbed, leading to insufficient water exchange and regulation with siltation in the waterways. Such weak hydrodynamic conditions resulted in insufficient biological exchange between the fishponds and the external marine area, leading to the shortage of bird food supply.

(4) Lack of shoals and islets

Safety is one of the critical factors for birds to select habitats, provided by a sense of openness on shoals and islets as key resting areas. The existing fishpond embankments and islets were densely covered by tall vegetation, with fast-growing

Table 3: Habitat needs of target waterbirds

Target waterbird		Waterbody	Water depth (cm)	Shoal and islet	Vegetation	Other	Source
Scolopacidae	Small	Continuous open water surface, low vegetation coverage, generally larger than 2 hm², regular shape	3 ~ 5	Soft soil, similar color as Scolopacidae	Low vegetation coverage, area proportion of shoals, water surface, and patches: 40%, 40%, 20%	Noise under 50 dB; flight initiation distance above 40 m	Refs. [10][17][32]~[38]
	Medium and large		Under 10				
Anatidae	Non-diving	Complex composition of water surface with aquatic vegetation patches	15 ~ 30	Soft sand and mud on shoals, part of sandy gravel substrate	Partially covered by aquatic vegetation, creating a safe environment	Slow water flow, foraging area current under 4.8 km/h	Refs. [32][38]~[41]
	Diving		25 ~ 200				
Ardeidae		Open water surface	15 ~ 40	Some sandy gravel bases on shoals for standing, not all silt	Vegetation coverage generally under 25%, mainly by trees, better with less closure	Noise under 60 dB	Refs. [14][17][42]
Rallidae		Open water surface with aquatic vegetation patches	· Foraging: under 10 · Resting: under 50	—	Vegetation patches on water surface (such as *Phragmites australis*, marsh grasslands) for activity concealment, rich submersed plants	—	Refs. [17][39]
Phalacrocoracidae		Continuous open water surface, low vegetation coverage	80 ~ 120	Small islets or logs and rocks in the water for perching	Water surface and aquatic vegetation ratio: 4:6 ~ 6:4	Slow water flow	Refs. [42][43]
Platalea minor		Continuous open water surface, low vegetation coverage	· Foraging: 5 ~ 10 · Resting: 5 ~ 25	Muddy shoals or substrates	Resting environment with some vegetation coverage around the water for a safe atmosphere	Turbid water, embankments or ridges for concealment are beneficial for foraging	Ref. [38]



4. Habitat needs for target waterbirds.

aquatic plants nearly occupied the entire water surface, such as *Phragmites australis*, *Eichhornia crassipes*, and *Alternanthera philoxeroides*, affecting the takeoff and landing of waterbirds and potentially providing concealment for predators. Additionally, there were a few small islets in the middle of the fishponds. With the rich vegetation on the islets had grown into groves, it lacks open space for resting.

(5) Excessive invasive plants

The embankments were overly covered with invasive and exotic plants. The trees were mainly exotic species including *Acacia mangium*. and *Acacia confusa* Although *Leucaena leucocephala* had been repeatedly cleared, there were still many seedlings sprouting. The ground cover mainly consisted of *Sphagneticola trilobata* with patches of *Bidens pilosa*. These fast-growing plants had disrupted the native ecological conditions.

(6) Heavy human activity disturbance

The Futian Mangrove Wetland is adjacent to urban built areas, and the northern fishponds were highly disturbed by urban environment and patrolling activities. The Xiasha area of Shenzhen has a high construction density, and was substantially affected by light and curtain walls; in addition, as the Guangshen Expressway closely runs along the boundary of the reserve, despite isolation strips, the noise in the fishponds, especially in the northern area, reaches about 70 dB, exceeding the noise tolerance level of most birds. The northern part of the fishponds is frequented by patrol vehicles, the sound and activities of which disturbed the bird habitat in the northern area.

4 Refined Ecological Restoration of Waterbird Habitats

4.1 Restoration Objectives

For an integral bird conservation area like the Futian Mangrove Wetland, it necessitates the synergy of restoration objectives for all fishponds while setting the specific goals for them each. According to the overall situation, the primary restoration goal was to provide a stable high-tide habitat for migratory waterbirds including *Platalea minor*, large Scolopacidae, and Anatidae; the secondary goal is to meet the full-life cycle habitat needs of local waterbirds, predominantly Ardeidae. The previously restored Fishponds No. 2 ~ 4 had effectively provided habitats for some Scolopacidae and Anatidae. However, it became a main issue that the habitat suitability for Shenzhen Bay's star bird species (*Platalea minor* and large Scolopacidae) needs to be improved for the restoration of the east bank of the Fengtang River, while providing composite habitats for various waterbirds reliant on the mangrove wetlands and Shenzhen Bay (Table 4).

4.2 Ecological Restoration Technical Strategies

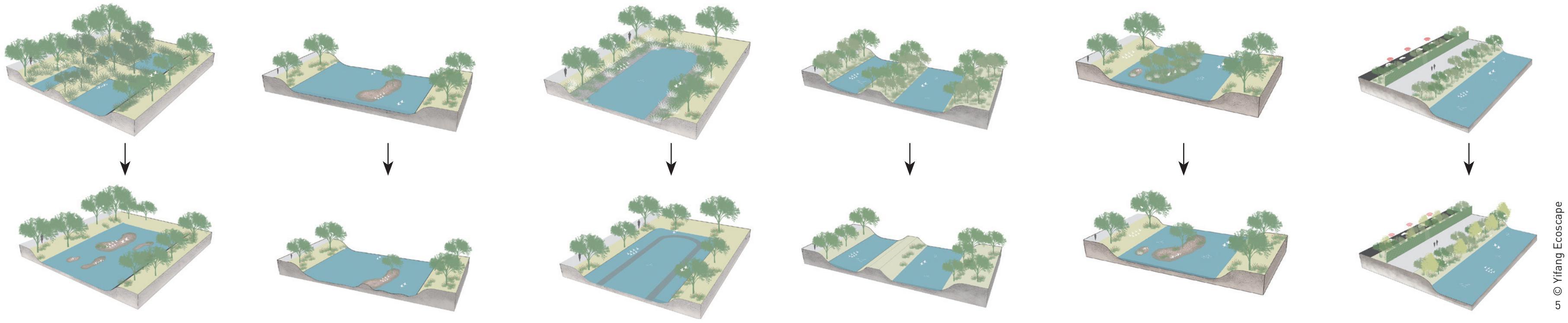
In response to the six identified common issues identified and informed by bird habitat requirement research, six ecological restoration technical strategies were proposed. These strategies, along with their adaptive approaches, can be selectively integrated in restoration efforts based on the specific problems and habitat needs of the target waterbirds, allowing for creating a customized strategy package (Fig. 5).

(1) Water surface expansion

To expand continuous open water surfaces preferred by waterbirds, current embankments in the middle of the fishponds should be removed or lowered, and converge segmented ponds. The integrated water surfaces should be larger than 2 hm^2, ideally

Table 4: Habitat types and major target birds of fishponds to restore

Fishpond	Habitat type	Major target birds
No. 5	High-tide habitat	*Platalea minor*, medium and large Scolopacidae, and other large wading birds
No. 6	High-tide habitat	*Platalea minor*, Ardeidae, and other large wading birds
No. 7	Traditional dike-pond	Various birds reliant on dike-ponds, such as Alcedinidae
No. 8	Traditional dike-pond	Anatidae and Ardeidae
No. 9	Deep-water habitat	Aythya
No. 10	Traditional dike-pond	Various birds reliant on dike-ponds, such as Alcedinidae
No. 11	Deep-water habitat	Local Ardeidae, Phalacrocoracidae, and Aythya
Northern Freshwater Pond	Wetland	Various birds reliant on wetlands
Typhoon Shelter Pond	Tidal flat	Various birds and animals reliant on wetlands



5. Six ecological restoration technical strategies.

maintaining a square shape. The proportion of shoal, water surface, and vegetation patch within a pond should be managed to be approximately 40%, 40%, and 20%, respectively.

(2) Water level control

Finely adjust the fishpond bed topography to create terraced bottoms, and install smart water gates to fulfill the varied water depth requirements of different waterbirds. During the migratory bird stopover season from October to next April, the water level should be controlled to form areas with varied water depths—less than 5 cm, 5 ~ 25 cm, 15 ~ 40 cm, and deeper than 1 m—catering to the resting needs of certain target waterbirds. During the rest time of the year, it should maintain a water depth of over 1 m to suppress the growth of *Phragmites australis*, thereby keeping the rational proportion of spatial elements within the water area.

(3) Hydrodynamic conditions improvement

This strategy involves dredging silt from the outward tidal channels, constructing internal circular deep channels, and modifying the elevation of water gate bottoms. The dredging degree of tidal channels is determined by the siltation situation, normally removing 30 ~ 50 cm thickness of silt. Along the pond perimeters, excavate deep channels normally requiring a bottom width of 5 m, a side slope at about 45°, and a depth over 2 m. The dimensions of these channels can be adjusted according to specific site conditions, for instance, progressively increasing the depth from the inlet towards the opposite end to optimize hydrodynamic conditions and foster suitable habitats for fish and shrimp. Moreover, aligning the bottom of the water gate with the fishpond bottom ensures complete drainage and can better facilitate the material and energy exchange with the surrounding environment, as well as improving inter-fishpond connectivity.

(4) Shoal transformation

On the basis of improved layout of water surface, construct 1 ~ 2 large central shoals and several small islets, with gentle sloping (5° ~ 25°) into the water and winding shoreline. Utilize the central embankment to form shoals, lengthening the foraging shoreline and expanding the resting area. Use the earth from lowering the embankment to construct small islets. In addition, clear the vegetation on existing islets and adjust the shape and elevation of the islets as required. The substrate for Scolopacidae should be soft soil that matches their body color, while the substrate for Anatidae should be soft sand and mud with sandy gravel.

(5) Adaptive vegetation management

Completely remove invasive plants such as *Leucaena leucocephala* and *Sphagneticola trilobata*, as well as aquatic plants like *Phragmites australis*. For islets within the fishponds, prune native trees to provide perching and nesting spaces for birds such as Ardeidae. For central embankment, clear the fast-growing, potentially invasive trees, transplant native tree species and selectively retain some tree islets. In terms of the southern pond embankments, clean up fast-growing and invasive tree species and keep native trees with proper pruning to ensure them not exceed the height of the mangroves, thereby forming a vegetation pattern lower and sparser in the south and higher and denser in the north.

(6) Disturbance control

To foster a secure environment with vegetation around the water and to shield the natural coastal wetland ecosystem from the large-scale urban municipal projects, the project proposed creating vegetative buffers to mitigate the disturbance of noise, lighting, and human activities. The barrier effect can be enhanced by expanding and elevating these buffers through on-site cutting-and-filling, and transplanting or locally densifying native plants. The widened part of the buffers should be raised to 1 m above the original terrain, gradually sloping into the water.

4.3 Refined Ecological Restoration Model

To improve the suitability of ecological restoration strategies for waterbird habitats, this project took into account the importance level of target waterbird conservation, the necessity of ecological restoration, and the resistance to restoration. It proposed three levels—high, medium, and low—of adaptive approaches tailored to the diverse habitat needs of waterbirds. Practically, by addressing the unique challenges and location features, a combination of these restoration strategies could be applied to forge a refined restoration plan for waterbird habitats in coastal wetlands (Table 5).

Table 5: Three levels of adaptive approaches for refined ecological restoration strategies

Strategy	High-adaptive approach	Medium-adaptive approach	Low-adaptive approach
Water surface expansion	· Water surface area larger than 3 hm^2 with a proportion of no less than 90% · Eliminate internal embankments to fully integrate all water areas, creating a large, open water surface	· Water surface area larger than 2.5 hm^2 with a proportion of no less than 80% · Lower internal embankments to visually form open water surfaces	· Water surface area larger than 2 hm^2 with a proportion of no less than 70% · Partially breach embankments for functional connectivity between water areas
Water level control	· Water level lower than 0.15 m · Adjust terrain of fishpond bottom into terrace, use smart water gates for real-time shallow water level control	· Water level between 0.15 ~ 0.4 m · Slightly adjust the terrain of the bottom of fishpond to form areas with varying depths	· Water level above 0.4 m · Maintain water level
Hydrodynamic conditions improvement	· High water exchange capacity · Dredge tidal channels to enhance hydrodynamic conditions for material and energy exchange	· Medium water exchange capacity · Lower water gate bottom elevation and construct circular deep channels inside the pond	· Medium water exchange capacity · Lower water gate bottom elevation
Shoal transformation	· Proportion of shoals larger than 40% · Construct central shoals and islets, increase shoreline complexity, lower slopes, and clear existing islet vegetation	· Proportion of shoals between 20% ~ 40% · Transform internal embankments into shoals and islets	· Proportion of shoals less than 20% · Partially lower embankments and clear vegetation to visually form shoals
Adaptive vegetation management	· Clear invasive plants and non-native plants from the embankments · Transplant native trees to create a vegetation pattern of lower and spaeser in the south to higher and denser in the north	· Clear invasive plants and non-native plants from the embankments · Retain native trees as tree islets and prune the branches of tall trees	· Clear invasive plants from the embankments · Clear aquatic plants like Phragmites australis within the fishpond
Disturbance control	· Noise lower than 50 dB · Expand and elevate the vegetation buffer through cutting-and-filling	· Noise lower than 65 dB · Densely plant existing vegetation buffers partially	· Noise lower than 85 dB · Deep channel as buffer zone instead of habitat for target waterbirds

NOTE

The proportion of water area refers to the area ratio of the water body to the fishpond; the proportion of shoals indicates the area ratio of the shoal to the fishpond.

4.4 Recent Restoration Practices

In the recently completed restoration projects, refined ecological restoration plans were determined by combining various restoration strategies for the target waterbirds of each fishpond (Table 6).

(1) Restoration plan for Fishpond No. 5

Fishpond No. 5, located adjacent to the Fengtang River estuary and the tidal flats of Shenzhen Bay, spans a total water area of 6.38 hm^2 in a square shape. It was divided into 5 sections by embankments, where each section's water surface falls short of 2 hm^2 with a depth of about 1 m. There had been an abundance of tall trees, and the water area had been significantly encroached upon by *Phragmites australis*, lacking open water surfaces, shoals, and islets. The northern section experienced substantial disturbances from patrolling and urban construction activities. Before restoration, limited wading birds such as *Egretta garzetta*, *Himantopus himantopus*, and *Platalea minor* were observed in southern small ponds during the drainage, indicating significant potential for ecological restoration.

Fishpond No. 5 was designated as a habitat for large wading birds like *Platalea minor*. The plan integrated all water areas into one continuous open water surface (Figs. 6, 7). With smart water gate installation and adjusted terraced pond bottom, the water level in the central area is maintained between 5 ~ 25 cm. Additionally, embankments were transformed into winding central shoals with gentler slopes to provide resting spaces for migratory birds. A deep channel (5-m-wide, 2-m-deep) was constructed along the perimeter to enrich the aquatic living environment and enhance hydrodynamic conditions. *Phragmites australis* and invasive plants were removed from the water surface and embankments, with native plants selectively conserved as tree islets. In the north, the vegetation buffer was widened and heightened to mitigate urban and human activity disturbances on birds (Figs. 6 ~ 9).

(2) Restoration plan for Fishpond No. 6

Fishpond No. 6, located close to the boundary of the reserve, presented a narrow, elongated shape, with a total area of 3.46 hm^2. It had been segmented into four water bodies by central embankments, all with high water levels. The embankments had been densely dominated by tall trees, suffering heavy external disturbances (Fig. 10). Ardeidae had been observed occasionally on the south side, suggesting a moderate potential for restoration. The goal was to provide a habitat for large wading birds including *Platalea minor* and Ardeidae.

The plan lowered the internal embankment to create a shoal, visually expanding the water surface. It involved localized adjustments to the micro-topography of the fishpond bottom and lowering the water gate elevation to regulate water levels. Tall trees were preserved for tree islets, while existing islets were transformed into shoals and islets. The earth excavated from breaking the embankment was used to construct new small islets in the southern part of the fishpond. The area adjacent to the northern

Table 6: Ecological restoration plans for four fishponds

Strategy	Water Surface Expansion	Water Level Control	Hydrodynamic Conditions Improvement	Shoal Transformation	Adaptive Vegetation Management	Disturbance Control
Fishpond No. 5	High-adaptive approach	High-adaptive approach	Medium-adaptive approach	High-adaptive approach	Medium-adaptive approach	High-adaptive approach
Fishpond No. 6	Medium-adaptive approach	Medium-adaptive approach	Low-adaptive approach	Medium-adaptive approach	Medium-adaptive approach	Low-adaptive approach
Northern Freshwater Pond	Low-adaptive approach	—	—	High-adaptive approach	Low-adaptive approach	—
Typhoon Shelter Pond	High-adaptive approach	—	High-adaptive approach	—	Medium-adaptive approach	—

boundary is designated mainly as a buffer, rather than a habitat for birds.

(3) Restoration plan for the Northern Freshwater Pond

The Northern Freshwater Pond, not directly connected to Shenzhen Bay, mainly relies on rainfall for water replenishment, distinguishing it as the only freshwater pond in the reserve. Covering an area of 4.3 hm^2, it had been segmented into 5 water areas by 4 embankments. Dense vegetation populated by invasive species, overtook the eastern water surface and embankments, making the area unsuitable for massive migratory bird habitation (Fig. 11). This pond had occasionally hosted various wetland-dependent bird species, including Rallidae, Alcedinidae, and Ardeidae. *Lutra lutra* had been observed under the bridge of the Fengtang River corridor, indicating significant restoration potential.

Given the unique spatial conditions of the Northern Freshwater Pond, its restoration was aimed at biodiversity enhancement,

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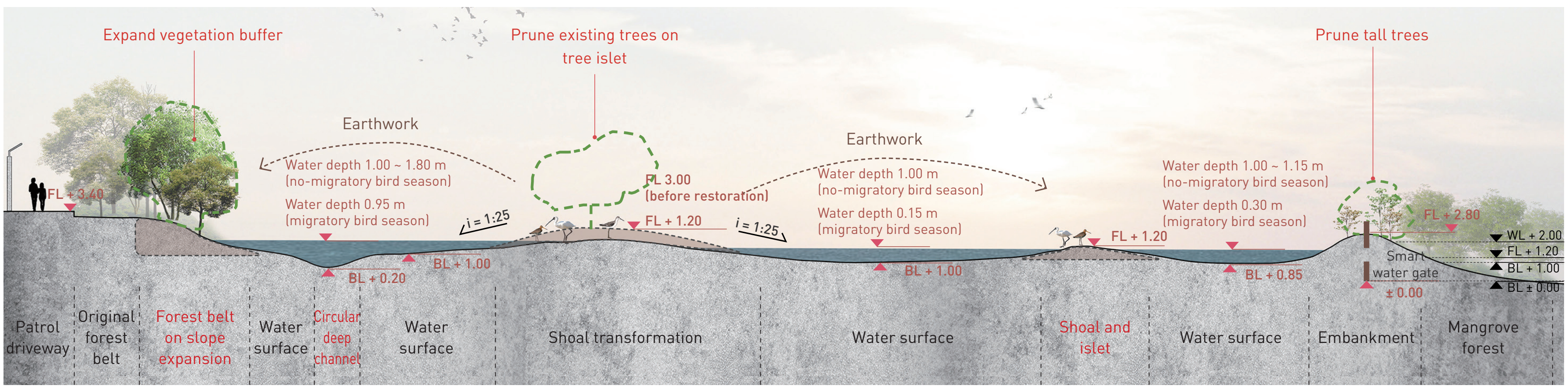
6

6. Restoration plan for Fishpond No. 5.
7. Section of restoration plan for Fishpond No. 5 ("i": slope; "FL": floor level; "BL": bottom level; "WL": water level).
8. Fishpond No. 5 before (left) and after (right) restoration.
9. Restoration outcome of Fishpond No. 5.



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10. Fishpond No. 6 before (left) and after (right) restoration.
11. The Northern Freshwater Pond before restoration (left) and after restoration (right).

primarily addressing limited water surface, lack of shoals and embankments, and excessive invasive plants. By partially breaking the embankments, the water system is functionally interconnected, enhancing the cycling capacity of materials and energy. Tall trees on the embankments are preserved, while invasive plants and aquatic vegetation like *Phragmites australis* were cleared. After removing vegetation, existing islets were enlarged and new ones were constructed, while increasing shoreline complexity and gentling the slope. The restoration provides habitats for various wetland-dependent birds and animals, and gradually recover its ecosystem functions (Fig. 11).

(4) Restoration plan of the Typhoon Shelter Pond

The Typhoon Shelter Pond is located about 200 m north of the tidal flats and directly connected to them through a tidal channel. Due to perennial siltation, the water surface had been fully invaded by *Acanthus ilicifolius*, making it difficult for migratory birds to use (Fig. 12). The intersection of the tidal channel and tidal flats of Shenzhen Bay served as a habitat for various waterbirds. It had significant potential for ecological restoration with Rallidae breeding in the northern forests. To effectively tackle with limited water surface, weak hydrodynamic conditions, and vegetation encroachment in the Typhoon Shelter Pond, and to fully restore it, high- and medium-adaptive approaches were adopted, involving dredging the tidal channel and clearing *Acanthus ilicifolius* within the pond to create an expansive open water surface and improve hydrodynamic conditions, thereby creating a tidal flat habitat for birds (Fig. 12).

5 Restoration Outcomes

The recent restoration project had been completed by the end of September 2022, coinciding with the arrival of migratory birds in Shenzhen Bay. Preliminary observations for the first stopover season indicated a significant increase in the variety and number of waterbirds across the fishponds. According to statistics, the variety of waterbirds in the reserve in 2022 increased by 33% compared with last year; the total number of waterbirds in the reserve increased from 27,392 to 37,079 (an increase of 35%) compared with 2016, and the variety increased from 53 to 80 species (an increase of 51%). Before restoration, only about 30 to 40 *Platalea minor* were observed in the entire reserve area during winter, while over 150 were observed in the winter of 2022, creating a new record for recent years[44]. Especially in Fishpond No. 5, over 50 individuals of *Platalea minor* can be observed each day (Figs. 13, 14). With small groups of Scolopacidae and Anatidae observed in Fishpond No. 5, the total estimated number of various waterbirds could reach 200 ~ 300, which is tenfold of the number before restoration. Compared with historical monitoring data from the Reserve Administration, national first-class protected species such as *Egretta eulophotes*, second-class protected

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12

12. The Typhoon Shelter Pond before (left) and after (right) restoration .
13. *Platalea minor* recorded in Fishpond No. 5 after restoration.
14. Waterbirds in the Futian Mangrove Wetland after restoration.

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13

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species like *Nettapus coromandelianus*, *Philomachus pugnax*, and *Hydrophasianus chirurgus* were returned the site for the first time in nearly 20 years. In December 2022, a flock of 29 *Ciconia boyciana* (national first-class protected species) were observed for the first time in nearly 30 years.

6 Conclusions and Perspectives

Focusing on the diverse habitat needs of target waterbirds, this project addresses site challenges specifically. It develops a refined waterbird habitat restoration model in high-density urban areas, which is applied and verified in the restoration project of the Futian Mangrove Wetland in Shenzhen. The implementation of the project effectively has increased the species and number of waterbirds and enhanced the function of Shenzhen Bay as a transit point for international migratory birds.

Building on the proposed restoration model, future efforts can delve into developing further refined management measures for coastal wetlands and waterbird habitats. It is recommended to persistently conduct smart monitoring and evaluation of waterbird habitats in the Futian Mangrove National Important Wetland in Shenzhen for real-time updates on habitat status and bird population dynamics. This will facilitate dynamic optimization and adaptive management, supplying scientific references and technological support for high-quality habitat restoration and the establishment of the International Mangrove Center. Additionally, it aims to bolster the Shenzhen Bay's significance for a wintering site and stopover of international migratory birds.

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Competing interests | The authors declare that they have no competing interests.

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基于自然的解决方案的高密度城市水鸟栖息地精细化生态修复模式探索——以中国深圳市福田红树林国家重要湿地为例

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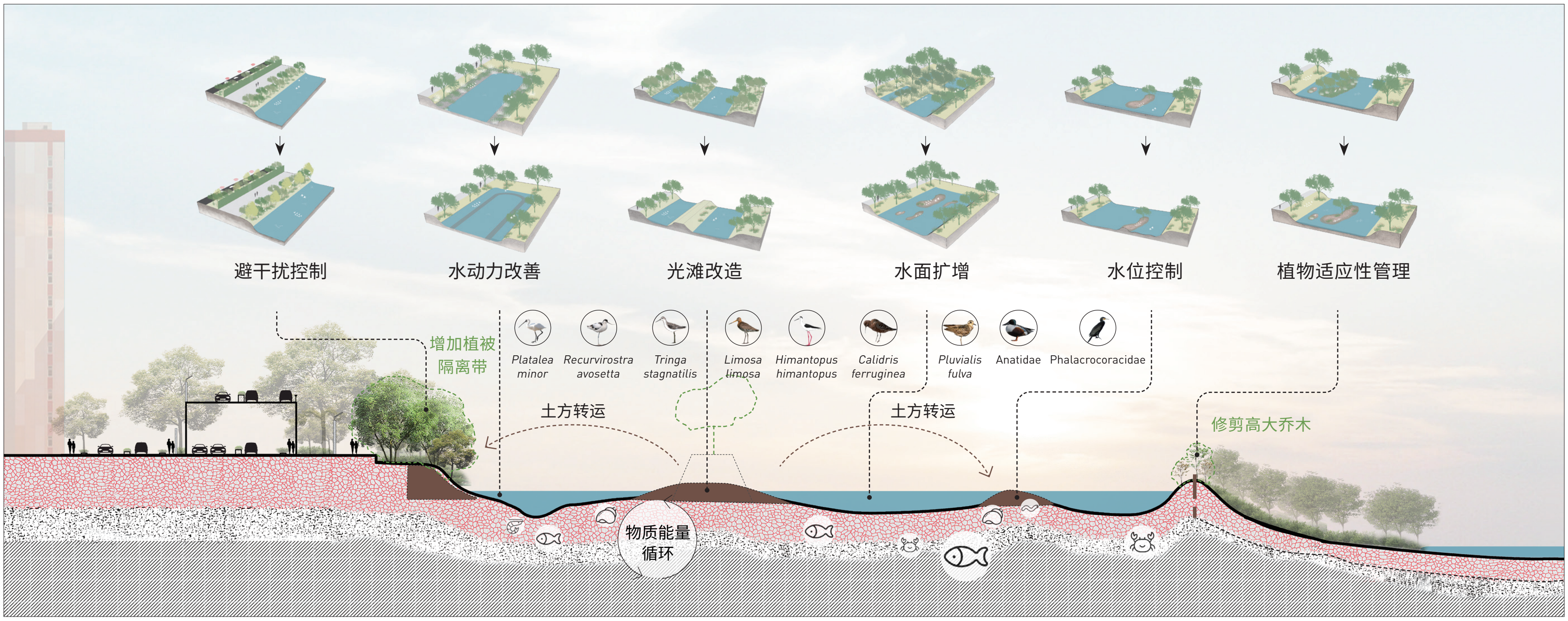
图文摘要



摘要

深圳湾是东亚–澳大利西亚国际候鸟迁徙的中转站和越冬地，也是社会经济发展活跃的高度城市化海湾。位于深圳湾东北部的福田红树林国家重要湿地是广东内伶仃福田国家级自然保护区的重要组成部分。作为中国面积最小且地处城市腹地的国家级自然保护区，其周边高强度城市环境对候鸟越冬栖息的影响显著，亟需针对水鸟保护的高质量、精细化生态修复。本项目以基于自然的解决方案为指导理念，建立了一套高密度城区滨海湿地水鸟栖息地精细化生态修复模式：通过研究鸟类行为和生境需求，提出了水面扩增、水位控制、水动力改善、光滩改造、植物适应性管理、避干扰控制六项策略，并建立了高、中、低适应途径以形成有效的策略包指导修复工程实施。修复工程实施后，黑脸琵鹭等目标鸟类的数量显著增加。2022年保护区内观测到的水鸟种类比上年增加33%，与2016年相比增加50.9%，海岸带生态系统服务功能明显增强。在中国城市更新进入存量发展的趋势下，这一修复模式可为滨海湿地鸟类保护生态修复提供借鉴，并为高质量建设深圳“国际红树林中心”提供重要支撑。

关键词

基于自然的解决方案；滨海湿地；生态修复；精细化生态修复模式；水鸟栖息地；生物多样性

文章亮点

- 探索基于自然解决方案的高密度城市滨海湿地精细化生态修复
- 结合文献研究及观测调研总结五大类水鸟的普适性生境需求
- 提出六项水鸟栖息地生态修复策略及其对应的高、中、低适应途径

基金项目

- 国家自然科学基金项目“海岸带城市绿色空间的韧性驱动机制研究——以粤港澳大湾区为例”（编号：52078004）
- 广东省基础与应用基础研究基金项目“粤港澳大湾区城市绿色基础设施韧性减灾效应与驱动机制研究”（编号：2021A1515012246）
- 深圳市科技计划项目“海岸带减污－增汇－应灾联动机制及协同增效技术研发与应用示范”（编号： KCXST20221021111416039）
- 深圳市科技计划项目库“河－湾生物栖息地修复和生态韧性构建技术研发”（编号：KCXFZ20211020164205009）

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1 背景

水鸟是对沿海城市生态环境变化高度敏感的种群[1][2]。滨海湿地的面积和质量都极大程度影响着本地水鸟的生物多样性和此地停歇的迁飞候鸟数量[3]。高密度城市开发建设和高强度人类活动导致海岸带人工化日趋严重，滨海湿地不断萎缩，对水鸟栖息地影响严重，候鸟种类和数量显著减少[1]。对于以粤港澳大湾区为代表的用地紧张的沿海城市而言，通过新增面积来开展滨海湿地和水鸟栖息地修复的难度越来越大，因此存量生境的精细化修复与提质增效尤为关键，这是在高密度城市中提升生物多样性和增强生态韧性的重要基础。

目前，针对水鸟栖息地的滨海湿地修复研究与实践日渐增多。主要技术方法有地形改造、噪声消减、植被种植、食物补充和水系统营造等[4]~[14]。例如，大卫·约佐等人提出使用疏浚材料，通过建造人工珊瑚礁、潮间带湿地和泥滩、鸟类岛屿等来修复鸟类栖息地环境[7]。这些技术方法能够有效提高当地的水鸟多样性，但部分方法偏重人工湿地的营造和管理，而非恢复自然湿地的潮汐调节功能；也有部分方法追求快速修复成效而忽视利用自然恢复的过程[15][16]。在水鸟的生态需求方面，研究表明不同种类水鸟因身体特征、生活习性差异而对栖息地需求不同，比如，雁鸭类（Anatidae）更偏好浅滩处有软质沙泥、部分沙石基底结构复杂的开阔水面，以及无植被覆盖的深水水域，而鹭类（Ardeidae）则更偏好栖息在乔木附近的水域[17]。因此，应针对不同水鸟的习性特点，实施精细化的修复方案[5]。现有栖息地修复方法中较少考虑目标水鸟，需求分析也相对简单，缺乏响应多种类水鸟习性的多目标修复方法。

近年来，基于自然的解决方案（Nature-based Solution，NbS）强调通过保护、管理或新建生态系统，辅助并利用自然发挥功能，以成本效益最佳的适应性方式有效应对复杂的社会挑战[18]~[20]，成为应对气候变化和增强韧性的有效途径。目前，NbS在生物多样性保护、湿地修复、河流生态系统保护等领域均有较多的研究与应用[8][21]~[24]，但在鸟类栖息地的精细化修复方面尚处于起步阶段。以NbS为指导理念，中国江苏盐城滨海湿地修复项目构建了鸟类避险区、游禽觅食区、涉禽觅食区、鱼类避险区和生态缓冲功能区[8]；中国浙江鉴洋湖圩田湿地修复项目以“保留－打破－整合”为设计理念，建立了“林－塘－田－湖－岛”复合生态湿地系统，提升鹭鸟的栖息地环境[24]；美国纽约州牙买加湾西部湖区生命海岸线改造项目增加了贝壳护岸结构、沉积物，种植湿地植物、控制岸线侵蚀，为濒危物种和迁徙鸟类提供栖息地[25]；美国路易斯安那州的中巴拉塔利亚沉积物分流最终恢复计划，通过重新连接密西西比河和巴拉塔利亚盆地河口，修复沿海湿地生境和生态系统功能[26]；加拿大尼亚加拉区采用生态系统适应性策略，利用生活岸线和海滩补沙措施保护水鸟类多样性[27]。上述案例虽然均将NbS作为指导理念，但对于具体方案如何落地的探索尚处于初步阶段，缺乏对明确模式方法的凝练。借助NbS创建滨海水鸟栖息地生态修复方法目前尚有较大发展空间，因此，本文以深圳市福田红树林重要湿地修复设计项目为例，研究高密度城市水鸟栖息地精细化生态修复模式，拟为滨海湿地生态修复理论和技术方法提供创新，丰富NbS在鸟类保护中的应用实践。

2 场地概况与总体修复模式构建

2.1 深圳市福田红树林国家重要湿地概况

深圳市福田红树林国家重要湿地（以下简称“福田红树林湿地”）是中国高密度沿海城市水鸟栖息地的典型代表，它位于广东省深圳市福

田区，紧邻香港米埔湿地，是广东内伶仃福田国家级自然保护区的重要组成部分，并先后被列入《2020年国家重要湿地名录》和《湿地公约》的“国际重要湿地”名录[28]。2022年11月5日，《湿地公约》第十四届缔约方大会宣布在深圳建设“国际红树林中心”[29]，福田红树林湿地则是其重要抓手。

福田红树林湿地是东亚－澳大利西亚国际候鸟迁徙路线中的越冬地和中转站，对全球鸟类保护意义重大。依据广东内伶仃福田国家级自然保护区管理局（以下简称“保护区管理局”）相关资料，每年有数10万只水鸟在深圳湾落脚，其中包括被列入世界自然保护联盟濒危物种红色名录（IUCN名录）的黑脸琵鹭（*Platalea minor*）、黑尾塍鹬（*Limosa limosa*）等13种水鸟。

深圳市福田中心区是深圳市乃至整个中国海岸带中的城市化程度较高的地区，该区域建设强度大、建筑高度高，各类人群活动频率高，对候鸟越冬栖息的影响较大。作为唯一地处城市腹地的国家级自然保护区，湿地与建成区之间缺乏缓冲区，保护工作难以突破现状用地范围，且保护区北部紧邻滨海大道和京港澳高速，道路交通对鸟类数量影响显著，使保护区面临较大的保护压力[30]。外围滩涂、红树林、基围鱼塘共同构成了福田红树林湿地的生态系统。基围鱼塘是重要的迁飞候鸟高潮位栖息地，如何在有限空间中实现高质量的水鸟栖息地精细化修复是福田红树林湿地面临的关键挑战。并且，在中国城市更新进入存量发展阶段的趋势下，栖息地精细化生态修复模式探索对城市高质量建设与提质增效具有重要支撑和借鉴意义。

2.2 场地现状

根据保护区管理局遥感影像资料，福田红树林湿地中的鱼塘总面积约63.17hm^2，主要包括12个基围鱼塘和1个避风塘。多年来，保护区管理局持续开展鱼塘修复工作，2022年前已修复鱼塘27.10hm^2（风塘河西岸1~4号塘）。本项目主要针对凤塘河东岸鱼塘（表1）开展整体修复，包括5~11号塘、北部淡水塘、避风塘，总面积36.07hm^2。其中，重点修复工程已于2022年3～9月完成施工，包括5号塘、6号塘、北部淡水塘和避风塘的生态修复（图1），基本实现凤塘河两岸1~6号鱼塘集中连片，便于生态管理。

2.3 总体修复模式构建

研究基于福田红树林湿地修复项目，创建针对高密度城市中多种目标水鸟需求的精细化生态修复模式，并在修复设计和工程实践中检验其效果。基于研究实践经验，本文构建了水鸟栖息地总体修复模式（图2）。首先，研究结合现有监测数据和现场调研观测，明确予以保护的目标水鸟种类；并通过文献研究和鸟类行为观测，分析目标水鸟的生境需求。其次，进行场地适宜性分析与问题诊断，针对水面面积、水位深度、水动力条件、滩岛形态、植物影响、城市及人类活动影响等方面提出精细化生态修复模式。最后，依据场地的具体条件综合选择包含高、中、低三种适应性途径的综合策略，并实施修复工程。

3 基于目标水鸟生境需求的场地研判

3.1 鸟类本底资源分析

研究通过多年监测数据与实地观测结合的方式开展鸟类本底资源分析。根据保护区管理局鸟类监测数据，截至2021年，福田红树林湿地内共记录到各类鸟类20目、60科、261种，其中国家一级保护鸟类有黑脸琵鹭、青头潜鸭（*Aythya baeri*）、小青脚鹬（*Tringa guttifer*）、黄嘴白鹭（*Egretta eulophotes*）、黑头白鹮（*Threskiornis melanocephalus*）、卷羽鹈鹕（*Pelecanus crispus*）、黑鹳（*Ciconia nigra*）、东方白鹳（*Ciconia boyciana*）等共13种，国家二级保护鸟类46种。其中黑脸琵鹭被列入《世界自然保护联盟濒危物种红色名录》中的濒危（EN）等级，而深圳湾的黑脸琵鹭数量超过其全球种群的1%，也是深圳的明星鸟种。

根据《福田红树林保护区1～11号鱼塘鸟类监测报告（2015—2018）》，2015年6月至2018年4月期间，保护区1～11号鱼塘共记录到鸟类120种，75 549只，总体呈现夏季少、冬季多的动态变化趋势。鸟类种群主要包括鸻鹬类（Scolopacidae，约占75%）、雁鸭类（约占13%）、鹭类、秧鸡类（Rallidae）、鸬鹚类（Phalacrocoracidae）等，其中优势种为反嘴鹬（*Recurvirostra avosetta*）、红脚鹬（*Tringa totanus*）、黑翅长脚鹬（*Himantopus himantopus*）、青脚鹬（*Tringa nebularia*）、弯嘴滨鹬（*Calidris ferruginea*）、泽鹬（*Tringa stagnatilis*）、金鸻（*Pluvialis fulva*）、琵嘴鸭（*Anas clypeata*）、绿翅鸭（*Anas crecca*）等。由于凤塘河东岸鱼塘尚未修复，依据2017至2018年的越冬鸟类观测数据，水鸟主要栖息在已修复的2~4号塘内（2号塘共计8 319只；3号塘共计4 353只，4号塘共计2 410只）（图3）。[31]

为实地验证东岸鱼塘修复前水鸟分布现状，项目团队于2022年1月12日和1月19日进行了样线观测：在深圳湾潮位较高（大于1.5m）时沿鱼塘外围固定线路步行观测，并记录鱼塘水位和水鸟活动情况。调查结果显示，仅8、9、11号塘中的水鸟数量超过50只，其余鱼塘仅在10只左右，主要为凤头潜鸭、白鹭（*Egretta garzetta*）、琵嘴鸭，还有少量黑翅长脚鹬、黑脸琵鹭等，与历史记录数据结果基本相符。

3.2 目标水鸟生境需求分析

根据鸟类监测数据和现场观察，确定福田红树林湿地五大类水鸟（鸻鹬类、雁鸭类、鹭类、秧鸡类和鸬鹚类）和国家一级保护动物黑脸琵鹭为目标水鸟。综合身长、生态型、居留型等因素，选择场地中种群规模较大的目标水鸟代表性物种（表2），分析其空间偏好和对人为干扰

表 1：凤塘河东岸各鱼塘概况

鱼塘	面积（hm^2）	小塘个数	水深（m）	生境概况
5 号塘	6.85	5	1~1.5	· 堤岸以高大乔木为主，入侵植物多 · 北部芦苇（*Phragmites australis*）侵占水面
6 号塘	3.46	4	1.5~2	· 堤岸植被以乔木灌木为主，入侵植物多 · 水域狭长，易受外界干扰
7 号塘	5.11	4	1.5~2	· 堤岸植被茂盛，入侵植物多 · 受城市交通噪声和灯光影响较大
8 号塘	3.93	2	2~2.5	· 堤岸植被茂盛，入侵植物多 · 塘内有岛屿
9 号塘	4.95	4	2~2.5	· 堤岸植被茂盛，入侵植物多 · 水域被塘内十字形堤岸分割，上有高大乔木
10 号塘	3.94	3	1~2	· 中部芦苇多，入侵植物多 · 东部逐渐陆地化，无对外潮沟
11 号塘	2.74	0	2~2.5	· 堤岸植被茂盛，以高大乔木为主 · 塘内有岛屿，乔木成林
北部淡水塘	4.30	5	0.3~0.5（旱季）／1（雨季）	· 堤岸植被茂盛，被高大茂密的植物围合，水面被水生植物侵占 · 无对外潮沟，雨水易于积蓄
避风塘	0.79	0	随潮水位变化	老鼠簕（*Acanthus ilicifolius*）生长侵占水面

耐受度，确定生境需求及其相关指标。

研究表明，除各类水鸟的特殊需求外，水鸟栖息地普遍需提供大片连续的开阔水面以满足集群飞翔及安全性需求；创造浅水位以满足觅食需求；营建一定比例的光滩、裸岛等供休息停留，同时在其周边需要有少量水生植物斑块（避免高大乔木）并避免噪声干扰等（表3、图4）。

3.3 场地生境问题分析

以水鸟栖息生境需求为标准，对红树林湿地基围鱼塘的水面面积、水位深度、水动力条件、滩岛形态、植被影响、城市及人类活动影响等方面进行适宜性分析，诊断得出现状鱼塘面临的六方面共性问题。

（1）水面小

开阔水面面积是影响水鸟栖息地使用情况的一项重要指标。凤塘河东岸大部分鱼塘面积为3~5hm^2，理论上可以满足鸻鹬类集群生活对连续开阔大水面的需求（2~3hm^2），但因各鱼塘内部被堤岸分隔成多个面积约1hm^2的小水塘，导致实际情况无法满足。

（2）水位深

水位深度是影响水鸟休息和觅食、决定湿地中水鸟种类丰富度的重要指标。目前大多数鱼塘水深均在2m左右，并呈现出从南到北、从西到东逐渐加深的趋势，东岸8、9、11号塘水位可达2.5~3m。

（3）水动力条件不足

鱼塘与深圳湾之间主要通过潮沟进行物质与能量交换，并在潮沟上建水闸调控水位。水闸在2008年之前建成，为传统的升降模式，且水闸箱体高于塘底，水体交换困难。由于水道淤积、水闸调控不足、水动力条件不足，鱼塘与外部海域的生物交换不够，鸟类食物单一、短缺。

表 2：目标水鸟代表物种概况

目标水鸟		代表物种	身长（cm）	生态型	居留型	人为干扰耐受度
鸻鹬类	小型鸻鹬类	弯嘴滨鹬（*Calidris ferruginea*）	18.0~23.0	涉禽	过境迁徙鸟	高
	大中型鸻鹬类	黑尾塍鹬（*Limosa limosa*）	36.0~44.0	涉禽	冬候鸟	高
雁鸭类	非潜水型雁鸭类	琵嘴鸭（*Anas clypeata*）	44.0~51.0	游禽	冬候鸟	中高
	潜水型雁鸭类	凤头潜鸭（*Aythya fuligula*）	40.0~47.0	游禽	冬候鸟	高
鹭类		白鹭（*Egretta garzetta*）	55.0~65.0	涉禽	以冬候鸟为主，少量夏候鸟和留鸟	中
秧鸡类		黑水鸡（*Gallinula chloropus*）	30.0~38.0	涉禽	冬候鸟，部分留鸟	高
鸬鹚类		普通鸬鹚（*Phalacrocorax carbo*）	84.0~90.0	游禽	冬候鸟	高
国家一级保护动物		黑脸琵鹭（*Platalea minor*）	60.0~78.5	涉禽	冬候鸟	高

注

数据来源于懂鸟网、保护区管理局访谈和现场观察。

（4）缺乏光滩、裸岛

安全性是鸟类选择栖息地的重要因素之一，光滩、小岛是水鸟休息的重点区域，开阔空间和光滩可以让鸟类感到安全。现状鱼塘中堤岸、岛屿上的植物高大郁闭，塘内芦苇、水葫芦（*Eichhornia crassipes*）、空心莲子草（*Alternanthera philoxeroides*）等水生植物生长过快、过密，几乎完全侵占水面空间，不利于水鸟飞翔升降且容易埋伏猛禽。鱼塘水域中央的小岛数量较少，且岛上植物生长茂盛，乔木已经成林，缺乏光滩小岛，无法为水鸟提供休息停留空间。

（5）入侵植物多

堤岸上入侵植物和外来植物数量众多，乔木以外来树种马占相思（*Acacia mangium*）、台湾相思（*Acacia confusa*）为主，银合欢（*Leucaena leucocephala*）虽然经过多次清理，仍有大量的小苗萌生；地被主要为南美蟛蜞菊（*Sphagneticola trilobata*），局部有白花鬼针草（*Bidens pilosa*）。外来植物和入侵植物生长速度快，破坏了本地原生态环境条件。

（6）人类活动干扰大

福田红树林湿地紧邻城市建成区，鱼塘北部受城市环境与巡护活动干扰大。深圳市下沙片区建设密度高，灯光和幕墙影响较大，且广深高速紧贴保护区边界，虽有道路隔离带，但鱼塘内尤其是北部区域噪声达70dB左右，超过了大部分鸟类的噪声耐受度。鱼塘北部常有巡逻车驶过，其声音和活动干扰北部片区的鸟类栖息。

4 水鸟栖息地精细化生态修复

4.1 修复目标

福田红树林湿地作为一个完整的鸟类保护区，各鱼塘修复目标需兼顾针对性与协同性。根据区域整体情况，红树林湿地生态修复主要目标是为以黑脸琵鹭和大型鸻鹬类为主、雁鸭类为辅的迁徙水鸟提供固定的高潮位栖息地；次要目标是满足以鹭类为主的本地水鸟的全生命周期栖息需求。早先完成的2~4号鱼塘修复已达一定成效，为部分鸻鹬类和雁鸭类提供了有效栖息地，但深圳湾明星鸟种——黑脸琵鹭和大型鸻鹬类的生境适宜性不佳。因此，本次凤塘河以东鱼塘修复需重点解决该问题，同时为其他依赖红树林湿地和深圳湾生活的各类水鸟提供复合型生境（表4）。

4.2 生态修复技术策略

针对场地的六大共性问题，以鸟类生境需求研究为依据，研究提出生态修复的六大策略。修复实践中可根据问题和目标水鸟需求，选取适

表 3：目标水鸟生境需求

目标水鸟		水域	水位	光滩裸岛	植物	其他	来源
鸻鹬类	小型	连续开阔水面、植被覆盖率低，一般大于 $2hm^2$，形状方正	3~5cm	土质软、颜色与鸻鹬类体色接近	植被覆盖率低、光滩、水面和植物斑块面积占比达到 40%、40%、20%	噪音小于 50dB；惊飞距离 40m 以上	参考文献 [10][17][32]~[38]
	中到大型		10cm 以下				
雁鸭类	非潜水型	水面与水生植物斑块构较为复杂的水域	15~30cm	浅滩处有软质沙泥、部分沙石基底	局部覆盖水生植物，遮蔽形成安全环境	水域流速宜缓，觅食区域流速小于 4.8km/h	参考文献 [32][38]~[41]
	潜水型		25~200cm				
鹭类		开阔水面	15~40cm	光滩处部分沙石基地供站立，不可全为淤泥	植被覆盖率一般不超过 25%，以乔木为主，低郁闭度为佳	噪音干扰一般不超过 60dB	参考文献 [14][17][42]
秧鸡类		开阔水面结合水生植物斑块	觅食：10cm 以下；休息：50cm 以下	—	水面上有植被斑块（芦苇丛、沼泽草地等）遮蔽活动，水下有丰富的沉水植物	—	参考文献 [17][39]
鸬鹚类		连续开阔水面、植被覆盖率低	80~120cm	水域中有小岛或木桩、石块等供站立	水面与水生植物比例保持在 4:6~6:4	水域流速宜缓	参考文献 [42][43]
黑脸琵鹭		连续开阔水面、植被覆盖率低	觅食：5~10cm；休息：5~25cm	淤泥质滩岛或塘底	休息环境水域周边有一定的植物遮蔽，营造安全氛围	水体浑浊，有堤坝或田埂等供隐蔽，更利于其觅食	参考文献 [38]

应途径进行组合，形成策略包（图5）。

（1）水面扩增

取消或降低现状鱼塘中央分隔堤岸，整合小鱼塘，扩增连续水面以形成鸟类偏好的开阔大水面。整合后水域面积需大于$2hm^2$，形状尽量方正，水域范围内的光滩、水面和植物斑块面积占比控制在40%、40%、20%为宜。

（2）水位控制

微调塘底地形，并结合智能水闸调控，在每年10月到次年4月的候鸟季，控制水位形成5cm以内、5~25cm、15~40cm、大于1m的梯级水深区域，分别满足各目标水鸟的栖息需求。非候鸟季维持水深大于1m，以抑制芦苇生长，进而维持水域范围内各空间要素的比例。

（3）水动力条件改善

通过清理对外潮沟淤泥，对内增加环形深水沟、降低水闸箱底高程等措施可有效改善塘内水动力条件。潮沟清淤深度根据淤积程度确定，通常清除滩涂表面30~50cm的淤泥。在鱼塘内部沿边缘开挖深水沟，通常底部宽5m，侧壁坡度约45°，深度大于2m，具体可根据场地条件作调整。如从水流进入端向远端越来越深，以便提升远端的水动力条件并为鱼虾提供生境。水闸箱底需与鱼塘底部持平，可完全排干鱼塘，方便塘内外的物质和能量交换，增加鱼塘之间的连通性。

（4）光滩改造

在水面格局确定的基础上，营造1~2个大型中央光滩及数个小型裸岛，滩、岛应以自然缓坡入水（设置5°～25°的半阳坡），并增加岸线曲折度。借助中央分隔堤岸形成中央光滩，延长水鸟取食岸线并增加休憩区域；利用降低堤岸产生的土方堆筑小岛；清理现状小岛植物，并调整其形态和高程。鸻鹬类栖息的滩岛材质选择土质软、颜色与鸻鹬类体色接近的基底，雁鸭类滩岛选择有软质沙泥、部分沙石的基底。

表4：工程所修复鱼塘生境类型及其目标水鸟

塘号	生境类型	主要目标鸟类
5号塘	高潮位栖息地	黑脸琵鹭、大中型鸻鹬类等大型涉禽
6号塘	高潮位栖息地	黑脸琵鹭、鹭类等大型涉禽
7号塘	传统基围生境塘	依赖基围鱼塘生活的各种鸟类，如翠鸟（Alcedinidae）等
8号塘	传统基围生境塘	雁鸭类、鹭类
9号塘	深水生境塘	潜鸭类（Aythya）
10号塘	传统基围生境塘	依赖基围鱼塘生活的各种鸟类，如翠鸟等
11号塘	深水生境塘	本地鹭鸟、鸬鹚类、潜鸭类
北部淡水塘	湿地生境塘	依赖湿地生活的各种鸟类
避风塘	滩涂生境塘	深圳湾各类水鸟

（5）植物适应性管理

彻底清理银合欢和南美蟛蜞菊等入侵植物，并清理芦苇等水生植物。修剪塘内小岛上乡土乔木树种的树枝，为鹭鸟等提供栖木和营巢空间；清理中央堤岸上速生且有入侵迹象的树种，迁移乡土树种，局部保留树岛；清理南部塘堤上速生且有入侵现象的树种，保留乡土树种并局部修剪，使其高度不超过红树林，形成南低北高、南稀北密的植被格局。

（6）避干扰控制

为了在水域周边营造有一定植物遮蔽的安全氛围，同时阻隔大型市政工程对滨海湿地自然生态系统的干扰，项目提出增加植物隔离带以削减城市噪声、光源和人类活动的干扰。通过鱼塘内填挖方平衡堆土加宽、加高植物隔离带，并排移栽或局部加密乡土植物，以增强隔离效果。植被隔离带加宽部分的土方堆坡应比原地表高1m以上，并以自然缓坡入水。

4.3 精细化生态修复模式

为加强生态修复策略对水鸟生境的适宜性，项目综合考量目标水鸟保护的重要性、生态修复的必要性、修复落地阻力三方面，提出高、中、低三种适应途径。在实践中可根据具体场地问题和特征，组合使用各修复策略中的适应途径，形成滨海湿地水鸟栖息地精细化修复方案（表5）。

4.4 近期生态修复工程实践

在近期已完成的生态修复工程中，项目借助不同修复策略针对各塘目标水鸟（表2）形成精细化生态修复方案（表6）。

（1）5号塘修复方案

5号塘紧邻凤塘河口和深圳湾滩涂，水域总面积6.38hm^{2}且形状方正，内部由堤岸分隔成5部分，每部分实际水面不足2hm^2，水深约1m，堤岸上高大乔木较多，水域内芦苇侵占严重，缺乏开阔水面和光滩小岛，北部受到巡护和城市建设活动干扰较大。修复前在南部小塘排水期发现少量白鹭、黑翅长脚鹬、黑脸琵鹭等涉禽类活动，表明生态修复潜力较大。

5号塘被定位为黑脸琵鹭等大型涉禽的栖息地，设计方案将所有水域完全整合成一个连续的开阔大水面（图6，7）。通过智慧水闸调控和梯级塘底调整将中心区水深控制在5~25cm，并将堤岸改造为中央光滩，增加岸线曲折度，降低坡度，为候鸟提供休息停留空间。沿鱼塘外缘增加5m宽、2m深的环形沟以丰富水生环境，改善水动力条件。清理水面芦苇和堤岸的入侵植物，以树岛的形式局部保留乡土植物。在北部加宽加高植物隔离带，以降低城市和人类活动对鸟类的干扰（图6~9）。

（2）6号塘修复方案

6号塘紧邻保护区边界，呈狭长形，总面积约为3.46hm^2，被中央堤岸分为4片水域，水位普遍较高，堤岸上高大乔木较多，受外界干扰大（图10），南侧偶有鹭类活动，修复潜力适中，目标是为黑脸琵鹭、鹭类等大型涉禽提供栖息地。

修复方案降低中央分隔堤岸形成裸堤，在视觉上营造开阔水面。局部调整塘底微地形，降低水闸箱底高程以调控水位。保留高大乔木形成树岛，改造现状小成为裸岛浅滩，利用改造堤岸产生的土方在塘中偏南部营造小岛，将北部紧邻边界的水域主要作为缓冲空间，不用作鸟类栖息地。

（3）北部淡水塘修复方案

北部淡水塘与深圳湾不直接连通，水源主要通过降雨补给，是保护区内唯一的淡水塘。该塘总面积4.3hm^2，被4条堤岸分隔为5片水域，堤岸植被茂盛（入侵植物多），东部水面被植物侵占，不利于大规模候鸟生活（图11）。塘内偶见秧鸡类、翠鸟类（Alcedinidae）、鹭类等各种依赖湿地生活的鸟类，凤塘河廊桥下有观测到欧亚水獭（*Lutra lutra*）活动，修复潜力较大。

根据北部淡水塘的独特空间条件，该塘的修复旨在提升生物多样

表 5：精细化生态修复策略的三种适应途径

修复策略	高适应途径	中适应途径	低适应途径
水面扩增	· 水面面积大于 3hm^2，占比大于 90% · 清除内部堤岸，完全整合内部各水域，形成完整开阔的大水面	· 水面面积大于 2.5hm^2，占比大于 80% · 降低分隔堤岸形成裸堤，在视觉上营造开阔水面	· 水面面积大于 2hm^2，占比大于 70% · 局部打断堤岸，实现各水域的功能性连通
水位控制	· 水位低于 0.15m · 调整地形形成梯级塘底，利用智能水闸实时调整保持浅水位	· 水位 0.15~0.4m · 对塘底局部微地形进行调整，形成不同水深区域	· 水位高于 0.4m · 保持现状水位
水动力条件改善	· 水交换能力高 · 潮沟清淤，提高塘内外物质和能量交换的水动力条件	· 水交换能力中等 · 降低水闸箱底高程，在塘内部增加环形深水沟	· 水交换能力中等 · 降低水闸箱底高程
光滩改造	· 光滩占比大于 40% · 堆筑中央光滩和裸岛，增加岸线曲折度，降低坡度，清理现状岛上植物	· 光滩占比 20%~40% · 将塘内分隔堤改造为光滩和裸岛	· 光滩占比小于 20% · 局部降低堤岸、清理植物，视觉上营造光滩
植物适应性管理	· 清理堤岸外来植物和入侵植物 · 迁移乡土乔木，形成南低北高、南稀北密的格局	· 清理堤岸外来植物和入侵植物 · 以树岛的形式保留乡土乔木，修剪高大乔木枝叶	· 清理堤岸入侵植物 · 清理塘内芦苇等水生植物
避干扰控制	· 噪声低于 50dB · 通过土方平衡，堆土加宽、加高植被隔离带	· 噪声低于 65dB · 局部加密现状植被隔离带	· 噪声低于 85dB · 将深水沟作为隔离带，非目标水鸟栖息地

注
水面占比指水域面积与该塘总面积的比值，光滩占比指光滩面积与该塘总面积的比值。

表 6：四个鱼塘的生态修复方案汇总

修复策略	水面扩增	水位控制	水动力条件改善	光滩改造	植物适应性管理	避干扰控制
5 号塘	高适应途径	高适应途径	中适应途径	高适应途径	中适应途径	高适应途径
6 号塘	中适应途径	中适应途径	低适应途径	中适应途径	中适应途径	低适应途径
北部淡水塘	低适应途径	—	—	高适应途径	低适应途径	—
避风塘	高适应途径	—	高适应途径	—	中适应途径	—

性，主要解决水面小、缺乏光滩裸岛和入侵植物多的问题。局部打断堤岸，实现鱼塘水系功能性联通，提高物质和能量循环能力。保留堤岸上的高大乔木，清理堤岸入侵植物和芦苇等水生植物。清理现状岛上植物并堆筑扩大裸岛，增加岸线曲折度，降低坡度，为依赖湿地生存的各种鸟类和动物提供栖息地，逐步恢复其生态系统功能（图11）。

（4）避风塘修复方案

避风塘位于滩涂北侧约200m处，通过潮沟与滩涂直接衔接，由于常年淤积，目前塘内老鼠簕完全侵占水面，候鸟难以使用水面（图12）。潮沟与深圳湾滩涂连接处是各类水鸟的栖息地，北部林下有秧鸡类繁育，生态修复潜力较大。为更有效地解决避风塘水面小、水动力条件较差和植物侵占水面的问题，选择中、高适应途径的修复策略：通过潮沟水道清淤和清理塘内老鼠簕，形成完整开阔水面并改善水动力条件，为鸟类创建新的滩涂生境（图12）。

5 修复实施效果

2022年9月底近期修复工程竣工，恰逢候鸟陆续抵达深圳湾。首个候鸟季的初步观测表明，各塘水鸟种类和数量均有显著提升。据统计，修复工程实施后，2022年保护区水鸟种类比上年增加33%；与2016年相比，2022年保护区水鸟总体数量从27 392只增加到37 079只（增加35.4%），水鸟种类从53种增加到80种（增加50.9%）。生态修复前，保护区整体在冬季通常只能观测到30~40只黑脸琵鹭，而2022年冬季则观测到150余只，创近些年新高[44]，尤其是5号塘修复后每天可监测到50余只黑脸琵鹭（图13，14）。5号塘内还发现小群鸻鹬类、雁鸭类活动，初步估计各类水鸟可达200~300只，鸟类数量是修复前的10倍以上。对比保护区管理局提供的历史监测数据，2022年观测到国家一级保护动物黄嘴白鹭、国家二级保护鸟类棉凫（*Nettapus coromandelianus*）、流苏鹬（*Philomachus pugnax*）、水雉（*Hydrophasianus chirurgus*）等，为保护区近20年来首次；2022年12月观测到29只国家一级保护野生动物东方白鹳（*Ciconia boyciana*），为保护区近30年来首次观测到东方白鹳集群。

6 结语与展望

本文基于目标水鸟对生境的多样化需求，有针对性地分析研判场地问题，创建了高密度城市水鸟栖息地精细化生态修复模式，并在深圳福田红树林湿地修复项目的应用中进行了验证。项目有效提高了水鸟的种类和数量，增强了深圳湾作为国际候鸟迁徙中转站的功能。

基于本文提出的修复模式，未来可进一步研究、制定滨海湿地和水鸟栖息地的精细化管理方法。建议在深圳福田红树林国家重要湿地持续开展水鸟栖息地智慧化监测评估工作，及时反馈栖息地状况和鸟情变化，开展动态优化和适应性管理，为高质量栖息地修复和国际红树林中心创建工作提供科学依据和技术支撑，进一步增强深圳湾作为国际候鸟迁徙越冬地和中转站的作用。

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图 1. 保护区鱼塘修复计划
图 2. 高密度城市水鸟栖息地精细化生态修复模式
图 3. 修复前水鸟分布情况
图 4. 水鸟生境需求
图 5. 生态修复策略示意图
图 6. 5 号塘生态修复方案图
图 7. 5 号塘生态修复方案剖面图（i 为坡度，FL 为完成面标高，BL 为池底标高，WL 为水面标高）
图 8. 5 号塘修复前（左图）后（右图）对比
图 9. 5 号塘修复效果
图 10. 6 号塘修复前（左图）后（右图）对比
图 11. 北部淡水塘修复前（左图）后（右图）对比
图 12. 避风塘修复前（左图）后（右图）对比
图 13. 5 号塘视频监控中的黑脸琵鹭
图 14. 生态修复之后福田红树林湿地中的水鸟